

Hint of relic gravitational waves in the Planck and WMAP data

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Relic gravitational waves (RGWs) leave well-understood imprints on the anisotropies in the temperature and polarization of cosmic microwave background (CMB) radiation. In the TT and TE information channels, which have been well observed by WMAP and Planck missions, RGWs compete with density perturbations mainly at low multipoles. It is dangerous to include high-multipole CMB data in the search for gravitational waves, as the spectral indices may not be constants. In this paper, we repeat our previous work [W.Zhao & L.P.Grishchuk, Phys.Rev.D **82**, 123008 (2010)] by utilizing the Planck TT and WMAP TE data in the low-multipole range $\ell \leq 100$. We find that our previous result is confirmed with higher confidence. The constraint on the tensor-to-scalar ratio from Planck TT and WMAP TE data is $r \in [0.06, 0.60]$ (68% C.L.) with the maximum likelihood at around $r \sim 0.2$. Correspondingly, the spectral index at the pivot wavenumber $k_* = 0.002\text{Mpc}^{-1}$ is $n_s = 1.13^{+0.07}_{-0.08}$, which is larger than 1 at more than 1σ level. So, we conclude that the new released CMB data indicate a stronger hint for the RGWs with the amplitude $r \sim 0.2$, which is hopeful to be confirmed by the imminent BICEP and Planck polarization data.

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I. INTRODUCTION

The relic (primordial) gravitational waves generated in the early Universe is a basic prediction in the modern cosmology, which depends only on the validity of General Relativity and Quantum Mechanics [1, 2]. The relic gravitational waves (RGWs) leave the imprints in all the cosmic microwave background (CMB) radiation anisotropy power spectra, including the TT, TE, EE and BB. In the near future, these provide the unique way to detect it in the observations. If the amplitude of the RGWs is large, (i.e. the tensor-to-scalar ratio $r > 0.1$), the CMB TT and TE information channels can dominate the detection, since the amplitudes of these spectra generated by RGWs are much larger than those of EE and BB [3, 4]. However, if $r < 0.1$, these channels become useless due to the cosmic variance, and the detection can only be done through the B-mode polarization [5, 6].

In the era before the release of the Planck polarization data, the detection (or constraint) of RGWs mainly depends on the CMB TT and TE channels, which has been done by many groups, including the WMAP and Planck teams. It is well known that the TT and TE power spectra generated by RGWs are significant only in the large scales, i.e. the low multipoles $\ell \lesssim 100$. However, in the previous analyses, nearly all the groups utilized the full CMB data till to the very high multipoles ($\ell_{\text{max}} \sim 1200$ for WMAP and $\ell_{\text{max}} \sim 2500$ for Planck), and assumed density perturbations with a constant or a running spectral index. This can easily overlook the contribution of RGWs, due to the degeneracies among various cosmological parameters (in particular, the degeneracy between r and n_s).

In 2006, Baskaran, Grishchuk and Polnarev noticed that the WMAP TE data are systematically smaller than the predictions of the best-fit cosmological model [7, 8], where the RGWs are absent, and argued that this might hint the existence of RGWs. In 2009, for the first time, one of us (W.Zhao) with Baskaran and Grishchuk carefully analyzed the three-year WMAP TE data in the low multipoles $\ell \leq 100$, and gotten the constraints on the quadrupole ratio $R = 0.149^{+0.247}_{-0.149}$ (note that the tensor-to-scalar ratio is $r \simeq 2R$) [9]. In addition, we have extended this analysis to the five-year and seven-year WMAP TT and TE data in the low multipoles $\ell \leq 100$, and found that the indication of RGWs were stabilized: five-year data give $R = 0.266 \pm 0.171$ [10], and seven-year data yield $R = 0.273^{+0.185}_{-0.156}$ [11]. In these analyses, we have adopted an approximate effective noises and the likelihood functions for the WMAP data, which are based on the exact Wishart distribution for the full-sky observables. However, these approximations were questioned by some authors (see for instance [12]). To clarify it, in paper [13], we adopted the commonly used CosmoMC numerical package to repeat the WMAP7 analysis. We found the maximize likelihood (ML) values are $r = 0.285$ and $n_s = 1.052$, and one-dimensional (1d) marginalized likelihood gives the constraints: $r = 0.20^{+0.25}_{-0.20}$ and $n_s = 1.064^{+0.058}_{-0.059}$. The CosmoMC approach reduced the confidence of the indications from approximately 2σ level to approximately 1σ level, but the indications do not disappear altogether.

Recently, Planck team released their CMB TT data, and shown some differences in the low multipoles compared with the WMAP data [14, 15]. In this paper, we shall repeat the analysis in [13] based on the combination of Planck TT data and nine-year WMAP TE data [16], and investigate the hint of RGWs in these new data, where the public

TABLE I: Results for n_s and r in Cases I-III

	Maximum likelihood		1-d likelihood	
	n_s	r	n_s	r (68% C.L.)
Case I ($n_t = -r/8$)	1.08	0.20	$1.13^{+0.07}_{-0.08}$	[0.06, 0.60]
Case II ($n_t = 0$)	1.09	0.25	$1.12^{+0.06}_{-0.08}$	[0.00, 0.52]
Case III ($n_t = n_s - 1$)	1.07	0.24	$1.11^{+0.05}_{-0.07}$	[0.05, 0.51]

CosmoMC numerical package is used for the data analysis. As anticipated, we found that the new data favor the gravitational waves with $r \sim 0.2$, and a blue tilted spectrum of density perturbation with $n_s \sim 1.08$. So, the new data stabilize what we found in the previous work [13].

II. DATA ANALYSIS METHOD AND THE PARAMETER CONSTRAINTS

Relic gravitational waves compete with density perturbations in generating CMB temperature and polarization anisotropies at low multipoles $\ell \lesssim 100$. Therefore we focus on the Planck TT data and WMAP9 TE data at $\ell \leq 100$. Limited by the data number in our analysis, it is impossible to determinate all the cosmological parameters together. Similar to our previous works [9–11, 13], we fix the background parameters at their best-fit values in the Λ CDM model [15]: $\Omega_b h^2 = 0.022032$, $\Omega_c h^2 = 0.12038$, $100\theta_{\text{MC}} = 1.04119$, $\tau = 0.0925$. The free parameters subject to evaluation by the data analysis are the parameters: the amplitude and the spectral index of density perturbations $\ln(10^{10} A_s)$, n_s , and the tensor-to-scalar ratio r . Note that, throughout this paper, we shall adopt the spectral amplitudes and the spectral indices at the pivot wavenumber $k_* = 0.002\text{Mpc}^{-1}$.

The value of n_t , the spectral index of RGWs, is very difficult to be determined by the current data. However, most inflationary models predict the nearly scale-invariant spectrum with $n_t \approx 0$. In *Case I*, the inflationary consistency relation $n_t = -r/8$, which is valid for the single-field slow-roll inflationary models, is adopted. By running the public CosmoMC code, we derive the following 3d ML values of the perturbation parameters:

$$r = 0.20, \quad n_s = 1.08, \quad \ln(10^{10} A_s) = 3.02. \quad (1)$$

The marginalized 1d results for these parameter (see also Table I) are

$$r \in [0.06, 0.60], \quad n_s = 1.13^{+0.07}_{-0.08}, \quad \ln(10^{10} A_s) = 2.94^{+0.14}_{-0.12}. \quad (2)$$

Note that, throughout this paper, we quote the mean values of 1d likelihood functions, and/or the uncertainties refer to the 68% confidence intervals. The 1d likelihood functions for n_s and r are plotted in Fig. 1. In the upper panel, the black curve shows a significant peak around $r \sim 0.3$, and $r = 0$ is excluded at more than 1σ level. Correspondingly, from the low panel we see that the spectral index n_s is larger than 1 at more than 1σ level. Interesting enough, we find that all these new results are compatible with the previous ones in [13], and also the indications of RGWs becomes higher for the better data.

In addition, we also consider other two cases: *Case II* with $n_t = 0$ and *Case III* with $n_t = n_s - 1$. The former case is nearly kept for the most inflationary models. The latter case with $n_t = n_s - 1$ is insisted by some authors [1, 8], which is valid if the expansion history of inflation can be approximated as a power-law form of the conformal time. The results for these two cases are presented in Table 1 and in Fig. 1 where the red and blue curves correspond to *Case II* and *Case III*, respectively. From Table 1 and Fig. 1, we see that the results in both *Case II* and *Case III* are quite similar to those in *Case I*. We conclude the assumption on n_t cannot significantly influence our results.

Before the end of this section, we need to mention that there is some awkwardness in the choice of the background parameters, as these are the parameters derived by Planck [15]. Actually the choice of these background parameters does not significantly affect the TT and TE spectra at low multipoles [17, 18]. As we know from our previous experiences [11, 13], the background parameters, if changed not too much, do not significantly affect the results. In order to make sure of it, we also fixed the background parameters to be WMAP best-fit values, and obtained similar results. Nevertheless, for the safety, we shall explicitly explore the issue of background parameters in a separate work [19].

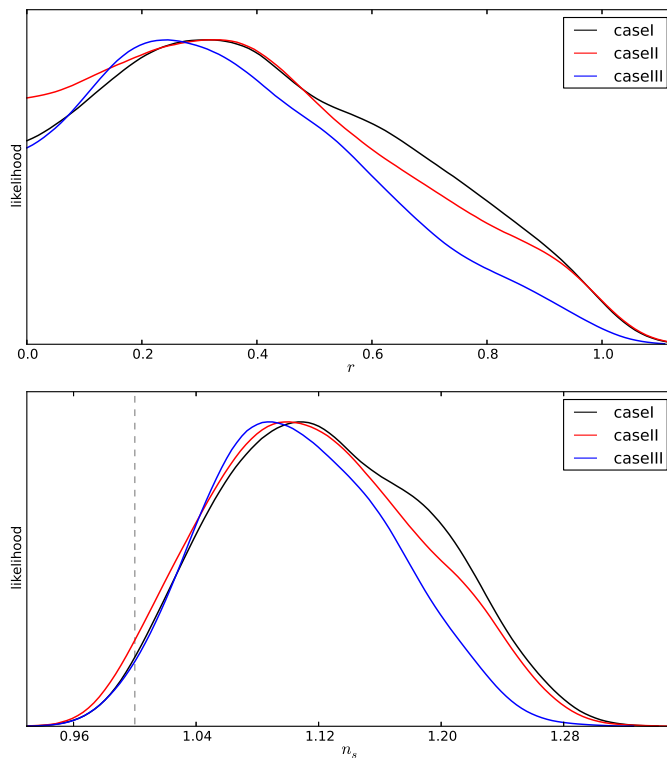


FIG. 1: One-dimensional likelihood functions for r (upper panel) and n_s (lower panel) in Cases I-III.

III. CONCLUSIONS

Relic gravitational waves provide the unique antenna to study the expansion history of the very early Universe. The detection of RGWs through their imprints in the CMB temperature and polarizations anisotropies is the only possibility in the near future, which has also been considered as one of the key tasks for the current and future CMB observations. In the well observed CMB TT and TE information channels, RGWs compete with density perturbations only in the low-multipole range. So, it is sensible to utilize only the low-multipole data in the search of RGWs, which is helpful to keep away from the unwarranted assumptions about density perturbations, and avoid the oversight of RGWs in the data analysis. In this paper, we repeated our previous analysis in [13] by considering the low-multipole Planck TT data, as well as the nine-year WMAP TE data. We found that, the new data give the constraint $r \in [0.06, 0.60]$ at 68% confidence level, which deviates from zero at more than 1σ confidence level. Meanwhile, the data favor a blue tilted spectra of primordial density perturbations with the spectral index $n_s = 1.13^{+0.07}_{-0.08}$ in the large scale. All these are consistent with what we found in [13]. We hope the forthcoming CMB polarization data of BICEP experiment and Planck mission could confirm our expectations.

Note: in the same day BICEP [20] released its data which indicates a discovery of the primordial gravitational waves with $r = 0.20^{+0.07}_{-0.05}$ and $r = 0$ disfavored at 7.0σ .

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